Formalism for Disturbance Rejection Design and Human-swarm Interaction

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Final Report

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The objective of the proposed research is to examine fundamental structural bounds on the disturbance rejection and human-swarm interaction properties of a network of diffusively interacting dynamic agents. These bounds are then employed to adaptively change or re-parameterize the network geometry in order to improve the disturbance resilience of the network while facilitating its manageability by human operator(s). The corresponding algorithms are examined in the context of centralized procedures where the network structure and its parameters are designed via suitable optimization algorithms, or analyzed via the probabilistic method, as well as a game theoretic approach where each agent or a subset of agents, based on the available local information, update the network structure and parameters in order to improve the overall disturbance rejection properties of the network and its effectiveness for being managed by human operator(s). In this venue, we address a number of issues at the core of networked multiagent networks with the aim of highlighting the intricate relationship between network structure and agent dynamics, on one hand, and network disturbance rejection properties and external manageability, on the other.

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Final Report

PI: Mehran Mesbahi, University of Washington, Seattle
Project Title: A Network-centric Formalism for Effective Disturbance Rejection Design and Human-swarm Interaction
AFOSR Control Number: FA9550-12-1-0203

The proposed project addresses the research areas that collectively lead to a unifying network-centric formalism for effective disturbance rejection design and human-swarm interaction. The research topics considered include:

(a) **Task 1 (Disturbance Rejection via Network Rewiring):** In this task we will derive fundamental graph-theoretic bounds on the input-output properties of a network of interacting homogenous dynamic agents adopting diffusion-like protocols for their coordination. In this direction, the network is first partitioned with respect to the network locations that are susceptible or have been exposed to disturbances or other inputs. The mechanisms via which disturbances at these locations map to critical network-level states are examined as network sensitivity functions. Our objective is to derive explicit graph theoretic relationships that highlight how various substructures in the network, e.g., its flow and cycle structure, sparsity, and degree distribution, shape these sensitivity functions and their system theoretic properties. In this venue, we will extend our preliminary results on relating the trace of the gramian for tree networks (connected graphs without cycles) to their respective effective resistances, to arbitrary graphs, which in turn, can provide the necessary insights in determining the role of cycles, and in particular their lengths, in shaping the disturbance rejection performance of the network. Such network centric insights, in turn, provide a novel mechanism for improving disturbance rejection properties of the multiagent systems that can complement existing approaches to single agent feedback design. For example, we will pursue local and global rewiring and re-parametrization algorithms to improve the network sensitivity functions subject to mobility constraints, disturbance profile, and portion of the network that is subject to disturbances. In the case of global rewiring, we plan to build upon the machinery previously utilized by the PI in improving spectral properties of state-dependent graphs via optimization-based approaches when permissible. Since this centralized approaches are not computationally feasible for large graphs particularly when the corresponding optimization models become non-convex, we will also examine a game theoretic technique for local network rewiring for performance improvement. Furthermore, we will provide structural guarantees on the sub-optimality of such local rewiring schemes for network sensitivity improvement for unweighted, weighted, and directed networks.

(b) **Task 2 (Effective Human-Swarm Interaction):** In this task, we build on the structural relationships obtained for network disturbance rejection properties to address effective network-centric design for human-swarm interaction. In this venue, we examine human operators' interaction with a large number of coordinating autonomous agents via interaction ports facilitated by a subset of agents. These ports induce a network partitioning that when paired with a set of agents' states or network-level critical states, constitutes a map that can be examined as the network-centric complementary sensitivity function. The operator theoretic behavior of this map in turn, captures how the network responds to human-operator(s), for example, in terms of following a command or responding to a gestural cue. Moreover, if we assume that the human operator(s) can observe a subset of agents or certain network output state, one can consider the fundamental graph theoretic bounds on an effective network-level feedback to influence the global behavior of the network. As such, it becomes important to characterize locations in the network that are most desirable for such an interaction (both inputs and outputs) in order to more effectively alleviate disturbances and strengthen human operators' influence.

(c) **Task 3 (Graph-theoretic Model Reduction):** In this part of the project, we aim to provide a graph-

theoretic formalism to obtained hierarchical reduced order models, with guaranteed input-output error bounds for the operation of multiagent networks. This will be achieved by proposing a graph theoretic approach for reducing the dimension of the representation for the multiagent/swarm behavior, with the advantage of facilitating low order controller design for external agents, e.g., human operators. System theoretic model reduction has a rich literature in systems and controls, for example, in the context of Hankel norm approximation and balanced realization/truncation techniques. These approaches can be successfully applied to multiagent diffusion-like protocols endowed with input and output ports. However, a distinct feature of the proposed work is examining the network features that allow for an effective and hierarchical model reduction scheme. This line of thought is intimately related to substructures that lead to network uncontrollability and unobservability. We also address issues such as network-theoretic balanced realization and graph theoretic means of reasoning about Hankel singular values for multiagent agent networks. These techniques in turn will be utilized to identify features in the network that do not significantly alter the network's input-output map over operational domains that are of interest to human operators.

(d) **Task 4 (Role of Heterogeneity):** In this task we will examine the role of heterogeneity in improving disturbance rejection properties of the network and how it can effectively be utilized for human-swarm interaction. For example, in a recent preliminary work of the PI, it has been shown that heterogeneity in the group coordination alters controllability and observability properties for certain class of dynamic networks, namely relative sensing networks. Moreover, for this class of networks heterogeneity in fact improves controllability properties of the network. In this project, we will further consider the role of heterogeneity in determining the network's system theoretic properties. This will be achieved by parameterizing the network's gramian structure using a heterogeneity index, that can further be used to design heterogeneous networks that are resistive to disturbances while responsive to human operators' generated inputs. We will also pursue a homogenization approach for approximating and reasoning about the operation of heterogeneous multiagent networks.

Summary of Accomplishments

Over the course of this project, we have been successful in a number of graph theoretic characterizations of a "robust" notion of network controllability and network performance. This research agenda aims to identify structural features in the network that allow for a set of inputs to indirectly control (or observe) the state of the nodes in the system under variations in the weights associated with the network interconnections. In this direction, we have characterized such notions as strong network controllability in terms of the unique (constrained) matchings in the network. This result in turn has provided a viable means of comparing different notions of network controllability (weak, strong, and those related to specific network protocols) for a wide range of networks, including networks that can be approximated by random graphs.

Another research thrust pursued in this project has been various notion of network controllability for *specific* classes of protocols, including diffusive and advective coordination algorithms. These have included state and output controllability, isolating the role of network symmetry and asymmetry, as well as how the network can be adapted to promote or resist external influence on certain performance metrics for the network, particularly those that connect with effective resistance of the network and properties of random walks. We have also proposed means of combining networks in such a way that certain properties of the composite network can be ascertain from those of the atomic/factor networks. The ramification of these contributions in the context of engineered and social networks have also been examined. One of the areas that is currently pursued by the PI is to collaborate with domain specific experts to extend the impact of the developed theory in areas such as energy networks, social networks, and cellular biology.

Applications of these theoretical results in the context of swarms of aerial and ground robotic systems have also been examined and tested in the laboratory. The PI has pursued establishing a unique testbed at the University of Washington for examining network-centric disturbance rejection and human-swarm interactions. This testbed serves not only as a prototype for validating the theoretical results obtained in this project but also to motivate a class of fundamental problems that have significant relevance in practical settings.

Under the task of model reduction, we have explored a network reduction technique based on fusing certain nodes and effective clustering techniques. The developed technique has then been examined in the context of system theoretic model reduction, and how network centric approaches connect with system theoretic guarantees.

The role of heterogeneity in coordination algorithm has yet provided another facet of our research program. In particular, we have examined how time-scale separation for robotic networks can be exploited to devise effective coordination algorithms for human-swarm interaction. The time-scale separation approach to examining complex network seems to be novel and promising direction for future investigation.

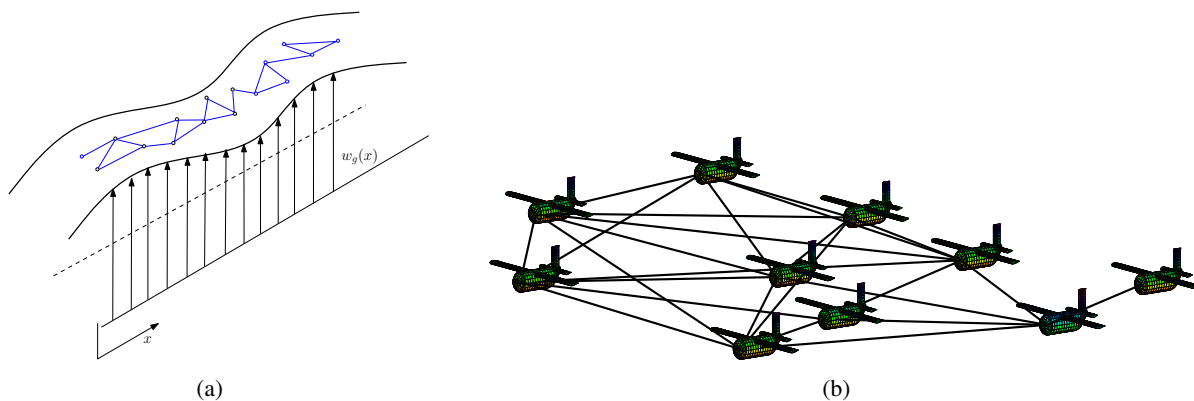(a)   (b)

Figure 1: An MAV network in gust; (a) gust gradient across the network, (b) MAVs in formation
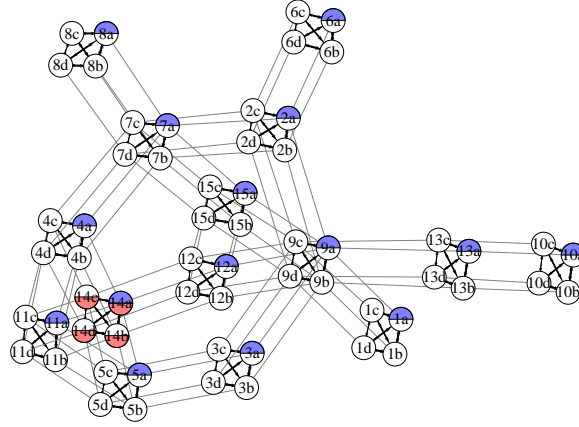
Figure 2: Composition of networks via Cartesian Products: the project aims to examine how system properties of networked systems change under various notions of network compositions

Publications

The following publications have been supported by this AFOSR grant:

- E. Schoof, A. Chapman and M. Mesbahi, Bearing-compass formation control: A human-swarm interaction perspective, *American Control Conference*, 2014.

- H. Shao and M. Mesbahi, Degree of Relative Influence for Consensus-type Networks, *American Control Conference*, 2014.

- A. Chapman and M. Mesbahi, On symmetry and controllability of multi-agent systems, *IEEE Conference on Decision and Control*, 2014.

- M. Mesbahi and M. Egerstedt, Graphs for Modeling Network Interactions, *Encyclopedia of Systems and Control*, Springer, 2014.

- A. Chapman and M. Mesbahi, UAV Swarms: Models and Effective Interfaces, in *Handbook of Unmanned Aerial Vehicles*, Springer, 2014.

- A. Chapman, M. Nabi-Abdolyousefi, and M. Mesbahi, Controllability and observability of network-of-networks via Cartesian products, *IEEE Transactions on Automatic Control*, 59 (10): 1-12, 2014.

- R. Dai, J. Maximoff, and M. Mesbahi, Optimal path planning for establishing connectivity in proximity networks, *IEEE Transactions on Aerospace and Electronic Systems*, 49 (3): 1968-1981, 2013.

- A. Chapman and M. Mesbahi, Semi-autonomous consensus: network measures and adaptive trees, *IEEE Transactions on Automatic Control*, 58 (1): 19-31, 2013.

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- A. Chapman, E. Schoof, and M. Mesbahi. "Advection on networks with an application to decentralized load balancing," *IEEE International Conference on Intelligent Robots and Systems*, 2012.

- R. Dai, J. Maximoff, and M. Mesbahi. Formation of connected networks for fractionated spacecraft, *AIAA Guidance, Navigation and Control Conference*, 2012.

- A. Chapman and M. Mesbahi. "Cartesian products of Z-Matrix networks: factorization and interval analysis," *Symposium on Mathematical Theory of Networks and Systems*, 2012.

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Abstract

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